Building and Environment 127 (2018) 204–210

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Numerical and experimental study on airborne disinfection by negative ions in air duct flow

Pei Zhou[a,b], Yi Yang[c], Gongsheng Huang[b], Alvin C.K. Lai[b,d,*]

[a] School of Civil Engineering, Hefei University of Technology, Hefei, Anhui, China
[b] Department of Architectural and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, China
[c] College of Engineering, Guangdong Ocean University, Zhanjiang, Guangdong, China
[d] City University of Hong Kong Shenzhen Research Institute, Shenzhen, China

ARTICLE INFO

Keywords:
Negative air ion
Disinfection
Bioaerosols
Ventilation duct
Indoor air quality

ABSTRACT

In this paper, we develop a mathematical model that aims (1) to predict the distribution of negative ions generated by an air ionizer installed in a ventilation duct and (2) to predict the efficiency with which it inactivates bacteria. The transportation equation for the negative ions was resolved combined with the bulk air velocity and the electric field.

The bacteria distribution was solved numerically by integrating the susceptibility constant, which was acquired from the experiments. Two types of bacteria (*Serratia marcescens*, *Staphylococcus epidermidis*) were aerosolized and released into a 9-m ventilation duct system. Inactivation efficiencies were calculated for inlet velocities from 2 to 6.5 m/s and for various ion intensities. The efficiencies for *S. marcescens* and *S. epidermidis* were 31.53% (SD, 11.4%) and 12.17% (SD, 0.43%), respectively, with susceptibility constants of 8.67×10^{-11} Colony-Forming Units (CFU)/ions and 2.72×10^{-11} CFU/ions, respectively. The modeling results matched those of the experiments well. The pressure penalty at the maximum velocity (6.5 m/s) was only 9 Pa. The results show that the use of negative ions has great potential to enhance indoor air quality by reducing airborne microorganisms in ventilation systems.

1. Introduction

According to the US Environmental Protection Agency, indoor air quality (IAQ) is one of the five most urgent environmental risks to public health [1]. Heating, ventilation, and air conditioning (HVAC) systems play a vital role in ensuring the indoor air quality inside such environments. Outbreaks of severe infectious diseases, from severe acute respiratory syndrome in 2003 to avian influenza and Middle East respiratory syndrome in recent years, indicate the importance of effective disinfection in ventilation systems to prevent extensive infections inside a building [2,3]. Ductwork systems provide a breeding ground for the potential reproduction and transmission of microorganisms [4]. Such microorganisms can survive and propagate throughout the entire building through sophisticated, interconnected ventilation duct systems, which may be lead to cross-infection of the occupants.

Conventional solutions for improvement of indoor microorganism levels are filtration or dilution. Commonly used medium-grade filters (minimum efficiency reporting value (MERV) of 8–10) are not effective in removal of small bacteria and viruses. In addition, filters can support active microbial growth if sufficient nutrients are present [5]. Energy considerations generally prevent the use of high-efficiency particulate air (HEPA) filters in commercial buildings.

Thus, to balance energy consumption and IAQ, in addition to physical removal approaches such as filtration and dilution, chemical/biological-based approaches for inactivation of airborne microorganisms have recently been developed and applied in HVAC systems. An alternative method using air ionizers for disinfection was developed in recent years. Park et al. [6] demonstrated the feasibility of the air ion disinfection approach for the reduction of aerosol particles in HVAC systems and found that this approach can be used to control IAQ. They showed that it is feasible to remove bioaerosols with a low-efficiency HVAC filter enhanced by continuous emission of unipolar air ions. Lee et al. [7–9] conducted similar experiments to determine the disinfection performance of air ions against aerosolized bacteria. Unipolar and bipolar ionizers were installed in a duct flow to evaluate the disinfection efficacy with different numbers of ionizers and the polarity effect.

There is an important parameter characterizes the susceptibility of bacteria disinfected with this kind of chemical/biological approach. It is often denoted as the susceptibility constant, *Z*, and its value depends

* Corresponding author. Department of Architectural and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, China.
E-mail address: alvinlai@cityu.edu.hk (A.C.K. Lai).

https://doi.org/10.1016/j.buildenv.2017.11.006
Received 12 August 2017; Received in revised form 31 October 2017; Accepted 3 November 2017
Available online 06 November 2017
0360-1323/

Nomenclature

A	Cross section area of the duct, m^2
C_i	the concentration of bacteria, CFU/m^3
CFU_{down}	the colony forming units of bacteria at downstream
C_{on}	the concentration of airborne after exposed to the negative ions
d	the distance between the ionizer and sampling point, m
D_p	Brownian diffusion coefficient for ion, m^2/s
I	the total ion current, A
i,j,k	unit vector
N_{ion}	the number of negative ions reaching single bacteria, ions/CFU
$Q_{capture}$	the flow rate when the bacteria was captured, m^3/s
S_i	Source term, CFU/(m^3·s)
S_{ion}	Source term of bacteria removed by negative ions, CFU/(m^3·s)
$t_{capture}$	bacteria capturing time, s
u	inlet velocity, m/s
v_d	deposition velocity, m/s
Z	the susceptibility constant, CFU/ions
Φ	potential difference, V
ε_0	the permittivity of free space, C^2/Nm^2
μ	dynamic viscosity, N·s/m^2
v_t	turbulent viscosity, m^2/s
A_w	the normal vector area of the cell face, m^2
CFU_{up}	the colony forming units of bacteria at upstream
C_0	the initial concentration of airborne, CFU/m^3
C_{off}	the initial concentration of airborne microorganisms
D_i	Brownian diffusion coefficient for bacteria, m^2/s
e	elementary charge, C
E	the electrical field, V/m
n	number of negative ions, ions/m^3
p	Pressure, Pa
$Q_{exposure}$	the flow rate when the bacteria was exposed to the ions, m^3/s
S_d	Source term of bacteria deposition onto walls, CFU/(m^3·s)
t	Time, s
$t_{exposure}$	the ion exposure time, s
V_{cell}	cell volume, m^3
$v_{s,i}$	particle settling velocity, m/s
Z_i	elaboration constant, m^2/J
ρ	air density, kg/m^3
ε_p	particle eddy diffusivity, m^2/s
μ_p	ion mobility, m^2/Vs
η	disinfection efficacy, %

primarily on complex biological characteristics of the airborne bacteria and the environmental conditions. Without knowing Z, it is not possible to predict the disinfection performance. Our group previously measured Z for a few bacteria under UV-C irradiation [10].

The disinfection mechanism of bacteria by air ions is usually summarized as a generated electrostatic force. Fletcher et al. proposed that unrecoverable electroporation plays a role in the disinfection effect of air ions [11,12]. Mendis et al. [13] proposed and modeled an electro-physical mechanism that involves the electrostatic disruption of a cell membrane. Digel et al. [14] explained the antimicrobial action of ions as a chemical modification of the surface proteins of bacteria. It is clear that the inactivation mechanism against microorganisms by air ions is still controversial.

There are a few experimental studies with air ionizers that aim to disinfect different types of bacteria, very few numerical studies were reported as well. Noakes et al. [15] and Fletcher et al. [12] developed a two-dimensional (2D) model to simulate the performance of negative ionizers in ventilated rooms, in which the electric field and ion balance equations were treated as user scalars and solved by a commercial computational fluid dynamics (CFD) tool. Mayya [16] developed a detailed mathematical model of air ions by considering the electric field, particle charging, ion transport, and wall loss. However, none of

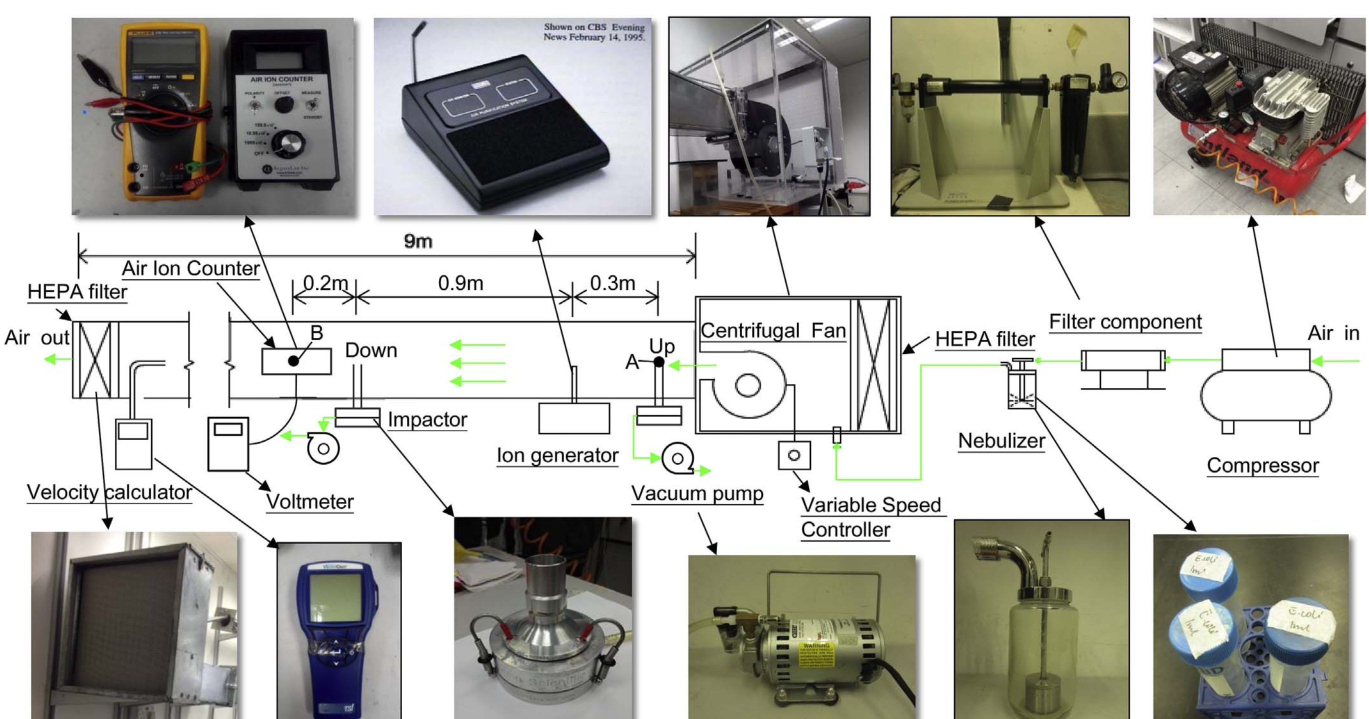

Fig. 1. The schematic lab-scale test setup.